The Terrestrial Planet Finder Coronagraph Performance Models

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Abstract

Understanding how to obtain image plane contrasts of a part in 10 billion requires a wide range of models, including ray-trace and polarization ray-trace analyses, Fourier Analyses, scalar and vector propagation, accurate representations of masks and stops, closed-loop pointing and wavefront control systems, thermal and mechanical models of the telescope and structure, and a means to bring the information derived from these models into an error budget that is traceable to engineering requirements.
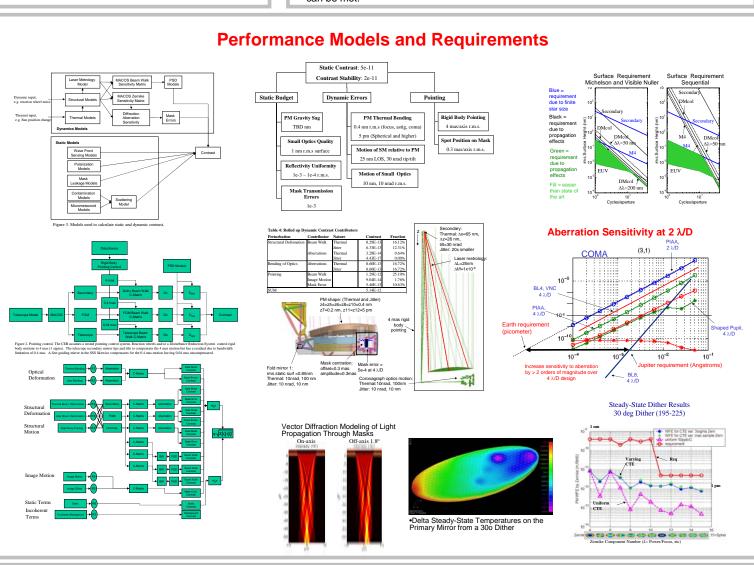
TPF-C Facts

An Earth-like planet is 10 billion times fainter than its parent star. A Jupiter-like planet is 1 billion times fainter than its parent star.

In the High Contrast Imaging Testbed in Bldg 318, we control scattered broad-band light to 1 part per billion.

TPF-C does NOT need supersmooth optics. HST or VLT class optics are adequate. Deformable mirrors in the coronagraph instrument flatten the wavefront.

TPF-C must be very stable for hours at a time. Modeling indicates the challenging requirements can be met.

Performance Models and Requirements

Figure 3. Models used to calculate static and dynamic contrast.

Figure 2. Pointing control. The CEB assumes a nested pointing control system. Reaction wheels and/or a Disturbance Reduction System control rigid body motions to 4 mas (1 sigma). The telescope secondary mirror tips and tilts to compensate the 4 mas motion but has a residual due to bandwidth limitation of 0.4 mas. A fine guiding mirror in the SSS likewise compensates for the 0.4 mas motion leaving 0.04 mas uncompensated.

Static Contrast: 5e-11
Contrast Stability: 2e-11

Static Budget
- **PM Gravity Sag** — TBD nm
- **Small Optics Quality** — 1 nm r.m.s surface
- **Reflectivity Uniformity** — 1e-3 – 1e-4 r.m.s.
- **Mask Transmission Errors** — 1e-3

Dynamic Errors
- **PM Thermal Bending** — 0.4 nm r.m.s (focus, astig, coma); 5 pm (Spherical and higher)
- **Motion of SM relative to PM** — 25 nm LOS, 30 nrad tip/tilt
- **Motion of Small Optics** — 10 nm, 10 nrad r.m.s.

Pointing
- **Rigid Body Pointing** — 4 mas/axis r.m.s.
- **Spot Position on Mask** — 0.3 mas/axis r.m.s.

Table 4: Rolled up Dynamic Contrast Contributors

Perturbation	Contributor	Nature	Contrast	Fraction
Structural Deformation	Beam Walk	Thermal	8.29E-13	16.12%
		Jitter	6.33E-13	12.31%
	Aberrations	Thermal	3.28E-14	0.64%
		Jitter	4.43E-17	0.00%
Bending of Optics	Aberrations	Thermal	8.60E-13	16.72%
		Jitter	8.60E-13	16.72%
Pointing	Beam Walk		1.29E-12	25.10%
	Image Motion		9.04E-14	1.76%
	Mask Error		5.46E-13	10.63%
SUM			5.14E-12	

PM shape: (Thermal and Jitter) z4=z5=z6=z8=z10=0.4 nm z7=0.2 nm, z11=z12=5 pm

4 mas rigid body pointing

Secondary: Thermal: Δx=65 nm, Δz=26 nm, tilt=30 nrad Jitter: 20x smaller

Laser metrology: ΔL=25nm Δf/f=1x10⁻⁹

Fold mirror 1: rms static surf =0.85nm Thermal: 10nrad, 100 nm Jitter: 10 nrad, 10 nm

Mask centration: offset=0.3 nm Thermal: 10nrad, 100nm Jitter: 10 nrad, 10 nm

Mask error = 5e-4 at 4 λ/D amplitude=0.3mas

Coronagraph optics motion: Thermal:10nrad, 100nm Jitter: 10 nrad, 10 nm

Surface Requirement Michelson and Visible Nuller / Surface Requirement Sequential

Blue = requirement due to finite star size
Black = requirement due to propagation effects
Green = requirement due to propagation effects
Fill = easier than state of the art

Aberration Sensitivity at 2 λ/D

Increase sensitivity to aberration by > 2 orders of magnitude over 4 λ/D design

Vector Diffraction Modeling of Light Propagation Through Masks

On-axis / Off-axis 1.8°

• Delta Steady-State Temperatures on the Primary Mirror from a 30o Dither

Steady-State Dither Results 30 deg Dither (195-225)

Publications

"Broadband Wavefront Control in a Pupil Mapping Coronagraph," S. B. Shaklan et al, Proc. SPIE 6693, 66930R (2007).
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"The Terrestrial Planet Finder Coronagraph Optical Surface Requirements," S. B. Shaklan, J. J. Green, and D. M. Palacios, Proc. SPIE 6265, 62651I (2006).
"Reflectivity and Optical Surface Height Requirements in a Broad-Band Coronagraph 1. Contrast Floor Due to Controllable Spatial Frequencies," S. B. Shaklan and J. J. Green, Appl. Opt. 45, 2163 (2006).
"The Terrestrial Planet Finder Coronagraph Dynamics Error Budget," S. B. Shaklan, L. Marchen, and J. J. Green, Proc. SPIE 5905, 59050D (2005).
"Low-Order Aberration Sensitivity of Eighth-Order Coronagraph Masks," S.B. Shaklan and J.J. Green, ApJ 628, 474 (2005).
"The Sensitivity of Shaped Pupil Coronagraphs to Optical Aberrations," J. J. Green et al, Proc. SPIE 5487 1358 (2004).
"Optimizing Coronagraph Designs to Minimize their Contrast Sensitivity to Low-Order Optical Aberrations," J. J. Green and S. B. Shaklan, Proc. SPIE 5170, 25 (2003).
"Stray-light Sources from Pupil Mask Edges and Mitigation Techniques for the TPF Coronagraph," D. Ceperley et al, Proc. SPIE 6271, 62711F (2006).